

Microscopic Formulation of Puff Field Theory

Sheikh Shajidul Haque and Akikazu Hashimoto

Department of Physics, University of Wisconsin, Madison, WI 53706

Abstract

We describe a generalization of Puff Field Theory to $p+1$ dimensions where $0 \leq p \leq 5$. We then focus on the case of $p = 0$, “Puff Quantum Mechanics,” and construct a formulation independent of string theory.

Melvin twist, also known as the T-s-T transformation, is a powerful solution generating technique in string and supergravity theories [1–6]. Melvin twist of flat spaces retains the simplicity of the flat space, giving rise to string theory whose world sheet theory is exactly solvable [7–12]. Melvin twists, in a context of D-branes and their near horizon limits, can be used to formulate wide variety of exotic field theories, including non-commutative gauge theories [13–19], NCOS theories [20–24], dipole theories [25–27], and β deformed superconformal theories [28].

Recently, “Puff Field Theory,” a new class of decoupled non-local field theory based on Melvin universe, was introduced by Ganor [29]. In the construction of PFT, the Melvin background is supported by RR field strength, but the decoupled theory is distinct¹ from the NCOS theories [23, 24]. In 3+1 dimensions, PFT preserves the spatial $SO(3)$ subgroup of the $SO(1, 3)$ Lorentz symmetry. The dual supergravity formulation of PFT, along the lines of [13], was constructed in [30], allowing physical feature of this model, such as the entropy as a function of temperature, to be computed at large ’t Hooft coupling. One of the main appeal of PFT is the fact that it is compatible with the symmetries of Freedman-Robertson-Walker cosmology. Some phenomenological aspects of PFT were studied recently in [31].

The Melvin deformed field theories enumerated earlier: non-commutative field theory, NCOS, dipole field theories, and β -deformed superconformal field theories all have concrete formulations independent of string theory. In contrast, only definition available for PFT, for the time being, is as a decoupling limit of fluctuations of D-branes in a Melvin geometry in type II string theory. The goal of this article is to provide an alternative definition of PFT which is independent of string theory. Our approach will closely parallel the formulation of Little String Theory and (0,2) superconformal field theory using deconstruction [32].

Let us begin by reviewing the construction of PFT as a decoupled theory on a brane in string theory [29, 30]. A convenient place to start is flat 9+1 geometry in type IIA theory, with N coincident D0-branes. Let us ignore the gravitational back reaction of the D0-branes for the time being. The M-theory lift of the IIA geometry is $R^{1,9} \times S_1$. Let us parameterize this geometry with a line-element of the form

$$ds^2 = -dt^2 + dr^2 + r^2 d\phi^2 + d\vec{y}^2 + dz^2 \quad (1)$$

where z is the M theory circle with periodicity $z \sim z + 2\pi R$, $R = g_s l_s$, and \vec{y} is a vector in seven dimensions. The r, ϕ parameterize a plane spanned by the remaining two coordinates in cylindrical coordinates.

Now consider performing a Melvin twist on ϕ with respect to shift in z . This amounts

¹See appendix A of [30] for a discussion of this point.

to deforming the line element by the amount η so that

$$ds_{11}^2 = -dt^2 + dr^2 + r^2(d\phi + \eta dz)^2 + d\vec{y}^2 + dz^2 . \quad (2)$$

Reducing this to IIA gives rise to a Melvin geometry of the form

$$ds_{IIA}^2 = (1 + \eta^2 r^2)^{1/2} \left(-dt^2 + dr^2 + \frac{r^2}{1 + \eta^2 r^2} d\phi^2 + d\vec{y}^2 \right) \quad (3)$$

along with some RR 1-form and a dilaton. Recalling that there were N D0-branes in the background, perform a T-duality along 3 of the y_i coordinates. The prescription of [29, 30] is to send $\alpha' \rightarrow 0$ keeping g_{YM3}^2 and $\Delta^3 = \eta\alpha'^2$ fixed. It is straight forward to reproduce the supergravity background of [30] by repeating this procedure, but including the gravitational back reaction of the D0-branes.

One issue which was not emphasized in the discussions of [29, 30] is that one can just as easily construct a generalization of PFT in $p + 1$ dimensions for $0 \leq p \leq 5$ by changing the number of T-dualities one performs, and scaling to keep $g_{YMp}^2 \sim g_s \alpha'^{(p-3)/2}$ to stay finite in the scaling limit. The resulting $p + 1$ dimensional field theory will preserve the $SO(p)$ subgroup of the Lorentz group.

To demonstrate the decoupling limit of PFT for general p more concretely, let us work out the supergravity dual of the $p = 0$ case explicitly. With the gravitational back reaction of D0 taken into account, (2) becomes

$$ds_{11}^2 = -h^{-1}dt^2 + h(dz - vdt)^2 + d\rho^2 + \rho^2(ds_{B(2)}^2 + (d\phi + \eta dz + \mathcal{A})^2) + \sum_{i=1}^5 dy_i^2 \quad (4)$$

where

$$h(\rho, y) = 1 + \frac{gN\alpha'^{7/2}}{(\rho^2 + \vec{y}^2)^{7/2}}, \quad v = h^{-1} \quad (5)$$

is the harmonic function of a D0-brane, and

$$d\Omega_3^2 = ds_{B(2)}^2 + (d\phi + \mathcal{A})^2 \quad (6)$$

is the standard Hopf parameterization of S^3 with the $B(2)$ being the base S^2 . In writing this geometry, we generalized the twist from being along the angular coordinate ϕ in a plane in (2), to being along the Hopf fiber of angular 3-sphere in R^4 spanned by *four* of the \vec{y} coordinates. This change essentially amounts to considering the F5 flux brane instead of F7 flux brane in the language of [5]. The latter choice has the advantage of preserving half of the supersymmetries. Now, reduce to IIA and take a decoupling limit, by scaling $\alpha' \rightarrow 0$ keeping $U = r/\alpha'$, $\Delta^3 = \eta\alpha'^2$, and $g_{YM0}^2 = g_s \alpha'^{-3/2}$ fixed. Note that

$$\nu = g_{YM0}^2 \Delta^3 \quad (7)$$

is a dimensionless and a finite quantity. This parameter will play an important role in the discussions below.

After taking the $\alpha' \rightarrow 0$ limit, we arrive at a solution of type IIA supergravity of the form

$$\begin{aligned}\frac{ds^2}{\alpha'} &= \sqrt{H + \Delta^6 U^2} \left(-H^{-1} dt^2 + dU^2 + U^2 ds_{B(2)}^2 + U^2 \left(d\phi + \mathcal{A} + \frac{\Delta^3}{H} dt \right)^2 + d\vec{Y}^2 \right) \\ \frac{A}{\alpha'^2} &= \frac{1}{H + \Delta^6 U^2} (-dt + U^2 \Delta^3 d\phi) \\ e^\phi &= g_{YM}^2 (H + \Delta^6 U^2)^{3/4}\end{aligned}\tag{8}$$

where

$$U = \frac{\rho}{\alpha'}, \quad \vec{Y} = \frac{\vec{y}}{\alpha'}, \quad H(U, \vec{Y}) = \alpha'^2 h(\rho, \vec{y}) = \frac{g_{YM0}^2 N}{(U^2 + Y^2)^{7/2}}\tag{9}$$

have finite $\alpha' \rightarrow 0$ limits.

This geometry has a natural form to correspond to a supergravity dual of decoupled theory on D0-branes. It is straight forward to generalize this construction to other values of p .

Let us refer to the decoupled theory for $p = 0$ as ‘‘Puff Quantum Mechanics.’’ If we set $\Delta = 0$, the metric (8) precisely reduces to the near horizon limit of D0-branes [33]. From the form of (8), one can infer that Δ deforms the matrix quantum mechanics of the decoupled D0-branes in the UV. It is also clear that the dynamics of the decoupled theory is somehow being modified by the RR 1-form potential in the background. In the remainder of this article, we will provide a prescription to define PQM independent of string theory.

One powerful tool in analyzing microscopic features of non-local field theories is the $SL(2, Z)$ duality. In the case of non-commutative field theory on a torus, an $SL(2, Z)$ duality is realized in the form of Morita equivalence [34]. If the deformation parameter, e.g. the non-commutativity parameter $2\pi\Delta^2$, is expressed in a suitably dimensionless form, e.g. $\Theta = \Delta^2/\text{Vol}(T^2)$, then for a rational value of Θ , one can find an $SL(2, Z)$ element to map this theory to a dual theory for which $\Theta = 0$. For non-commutative field theories, the $\Theta = 0$ theory corresponds to the standard non-abelian gauge theory on T^2 with a ’t Hooft flux [35]. Various $SL(2, Z)$ duals have non-overlapping regimes of validity as a function of energy, giving rise to a structure resembling a duality cascade [36]. For all rational values of Θ , it is the $SL(2, Z)$ dual with vanishing Θ which is effective in the deep UV.

Analogous $SL(2, Z)$ structure exists for PFT [30]. In the context of PQM, this structure is made most transparent by performing a modular transformation on the complex structure

of the torus defined by ϕ and z in (4), i.e.

$$\begin{pmatrix} d\phi \\ \frac{dz}{R} \end{pmatrix} \rightarrow \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} d\phi \\ \frac{dz}{R} \end{pmatrix} \quad (10)$$

If the dimensionless parameter

$$\nu = g_{YM0}^2 \Delta^3 = \eta R = -\frac{b}{d} \quad (11)$$

is a rational number, this $SL(2, Z)$ will map (4) to

$$\begin{aligned} ds^2 &= -h^{-1/2} dt^2 + h^{1/2} \left(d\rho^2 + \rho^2 ds_{B(2)}^2 + \rho^2 \left(\frac{d\phi}{d} + \mathcal{A} \right)^2 + d\bar{y}^2 \right) \\ A &= -cRd\phi - vdt \\ e^\phi &= h^{3/4} . \end{aligned}$$

Other than the seemingly innocent 1-form $A = cRd\phi$, this is just a Z_d orbifold of D0 which defines a local theory in the decoupling limit. The $SL(2, Z)$ also changed the rank of the gauge group from $U(N)$ to $U(d^2 N)/Z_d$, as well as acting on g_{YM0}^2 .

Let us refer to the RR deformed D0-brane quantum mechanics as “Twist Quiver Quantum Mechanics.” Our goal is to determine how the RR background affects the dynamics of TQQM.

In order to access the effect of form fields on the dynamics of open string states, it is convenient to go to a dual frame where the form field in question is mapped to an NSNS 2-form so that one has access to an explicit NSR sigma model. In order to accomplish this, let us momentarily embed the Z_d ALE orbifold spanned by ρ , $B(2)$, and ϕ in a Taub-NUT. This is a UV modification which can be removed later. The reason for embedding into the Taub-NUT is to facilitate the T-duality along ϕ . This T-duality will map the Taub-NUT to NS5-branes, and the D0-brane to a D1-brane. They are oriented as follows:

	0	1	2	3	4	5	6	7	8	9
D1		•	•							
NS5	•			•	•	•	•	•	•	

The system is to be visualized as a system of dN D1-branes sprinkled with d NS5 impurities, which is illustrated in figure 1. The RR 1-form potential $A = \frac{\varepsilon}{d}(dR)d\phi$ becomes the RR axion $\chi = \frac{\varepsilon}{d}$ under this duality.

In order to map the RR axion into NSNS 2-form, we further compactify two directions, parallel to the NS5-brane world volume but orthogonal to the D1. This compactification will also deform the theory in the UV, which we will remove at the end of the construction. T-dualizing along these two directions, followed by S-duality will lead to a system consisting

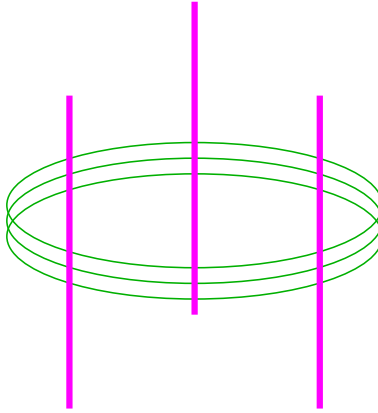


Figure 1: Configuration of dN D1-brane and d NS5 impurities obtained by T-dualizing the background (4) along the ϕ direction. There is also a RR axion $\chi = \frac{c}{d}$ in this background.

of dN D3-branes on T^2 , with d D5 impurities extended along the T^2 and localized in the remaining spatial coordinate of the D3, in a background a constant NSNS 2-form along the T^2 .

	0	1	2	3	4	5	6	7	8	9
B -field			\equiv	\equiv						
D3	•	•	•	•						
D5	•		•	•	•	•	•			

Except for the compactification and the B -fields, this is precisely the impurity model of Karch and Randall [37] whose detailed microscopic formulation was given in [38].

Of course, to isolate the PQM/TQQM dynamics, we are only interested in the deep IR where only the dimensionally reduced dynamics matters. We can take advantage of this fact to further reformulate this system by performing additional dualities.

Consider T-dualizing along the world volume of the D3-brane in the x_1 direction along which the D1 was originally oriented. This will map the D3-brane to a D2-brane localized in a circle. Its covering space is an infinite array. The impurity D5-branes are mapped to an extended D6. The T^2 along which the B -field was oriented is left intact.

	0	1	2	3	4	5	6	7	8	9
B -field			\equiv	\equiv						
D2	•		•	•						
D6	•	•	•	•	•	•	•			

This configuration is illustrated in figure 2.a. What we have done is to exchange the Kaluza-Klein mode associated with the x_1 direction to a tower of massive W bosons in a $U(\infty)/Z$ gauge theory along the lines of [39].

Let us now employ a trick of presenting $U(\infty)/Z$ as a limit of $U(N)/Z_N$. Simply consider

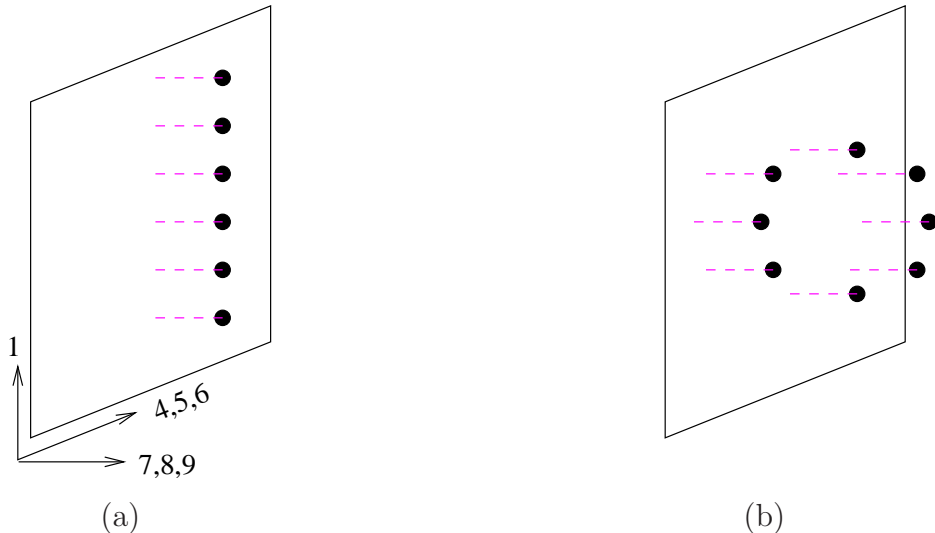


Figure 2: (a) T-dual of Defect Field Theory. The D2-branes is localized in a circle. In the covering space, it corresponds to a $U(\infty)/Z$ theory corresponding to an array of D2-branes in a background of D6-branes. (b) The infinite array can be arrived as a limit of a circular lattice by scaling the radius and the number of branes keeping the linear density of the branes fixed.. For the sake of illustration, the D2-branes appear separated from the D6-branes along the 7,8,9 directions in the figure. The actual configuration we consider, the D2 and the D6 branes are coincident along the 7,8,9 directions.

arranging N D2 in a circular, instead of the linear, pattern as is illustrated in figure 2.b. This is essentially a technique to simulate T-duality via deconstruction along the lines of [32].

What we have now is a configuration of D2 in Coulomb branch, in a background of D6-branes. This is essentially the configuration which gives rise to 2+1 SYM with flavor, considered in [40]. The only novelty here is the fact that the world volume of D2 is compactified on a torus, and that there is a B -field oriented along it.

Following the duality chain, it should be clear that each dot in figure 2 should correspond to dN D2-branes. It is quite natural therefore to interpret the c/d units of B -flux as giving rise to 't Hooft's fractional flux on the D2-brane world volume gauge theory [35,41–43].

There is one subtlety with this interpretation. In order for the 't Hooft flux to exist as a consistent field configuration, it is necessary for all the fields in the theory to be invariant with respect to the center of the gauge group. The flavor matter which arise in our setup due to the presence of the D6-brane, is in the fundamental representation with respect to the gauge group and does not satisfy this requirement.

A moment's thought, however, suffices to address this issue. One simply needs to recall that the 2-6 strings are actually in a bifundamental representation of the D2 and the D6-

brane gauge fields. Since there are d D6-branes in the configuration illustrated in figure 2, it can also support a flux in the amount of $\int B = c/d$. From the point of view of the 2+1 dimensional Yang-Mills theory, this amounts to twisting with respect to gauge and the flavor group of the bifundamentals. In other words, we parameterize the color and flavor indices of the bi-fundamental as $\Phi_{i,c;f}$ where $i = 1 \dots N$, $c = 1 \dots d$, and $f = 1 \dots d$. As the notation suggests, (i, c) are the color indices and f is the flavor index. To these bi-fundamental fields, we impose the boundary condition

$$\begin{aligned}\Phi_{i,c;f}(x + L_2, x_3) &= U_{c,c'}\Phi_{i,c';f'}(x_2, x_3)U_{f',f}^{-1} \\ \Phi_{i,c;f}(x_2, x_3 + L_3) &= V_{c,c'}\Phi_{i,c';f'}(x_2, x_3)V_{f',f}^{-1}\end{aligned}\tag{12}$$

where U and V are $d \times d$ 't Hooft matrices [35] satisfying

$$UVU^{-1}V^{-1} = e^{2\pi ic/d} .\tag{13}$$

In fact, precisely this form of twisted matter theory have been used before by Sumit Das in the context of large N twisted reduced models [44]. See also [45–48] for discussions on related issues.

Of course, since we have performed various UV deformation of the original PFT to get to this stage, one must take the appropriate scaling limit to decouple these effects. The fact that the decoupled supergravity dual solution (8) exists provides us with the assurance that such a limit does exist. Because the chain of duality involved S-duality at one point, what we are doing is similar in spirit to defining NCOS as the strong coupling limit of NCSYM [20–22].

In summary, we have shown that PQM is a scaling limit, of a large N deconstruction limit, of 2+1 dimensional SYM, with 't Hooft flux, and matter in the fundamental representation, with twisted flavor. The derivation relied on a lengthy chain of dualities and manipulations in string theory. Nonetheless, the formulation of the theory in its final form does not rely on any string theory concepts. While this definition is not especially useful for most practical applications, it does provide a concrete formulation of the theory whose only other formulation known today is as a decoupling limit of D-branes in a Melvin universe background. [29, 30].

The color/flavor twisted 2+1 dimensional theory (12) might be an interesting theory in its own right to explore further. These theories are related via Morita equivalence to non-commutative field theories with matter [49, 50], whose dual supergravity solution was briefly described in [40]. It might also be interesting to explore how the twists and non-commutativities modify the Intriligator Seiberg mirror symmetry of three dimensional gauge theories [51].

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